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Techno-economic evaluation of bioenergy production from anaerobic digestion of by-products from ethanol flex plants

Miriam Tena [a], Luz S. Buller [b], William G. Sganzerla [b], Mauro Berni [c], Tânia Forster-Carneiro [b], Rosario Solera [a], Montserrat Pérez [a,*]

[a] Department of Environmental Technologies, IVAGRO, Faculty of Marine and Environmental Sciences (CASEM), University of Cadiz, Pol. Rio San Pedro s/n, 11510, Puerto Real, Cadiz, Spain

[b] School of Food Engineering (FEA), University of Campinas (UNICAMP), Monteiro Lobato St., n. 80, 13083-862 Campinas, SP, Brazil

[c] Interdisciplinary Center on Energy Planning (NIPE), University of Campinas (UNICAMP), Cora Coralina St., n. 330, 13083-896 Campinas, SP, Brazil

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ABSTRACT

Ethanol production implies in by-products generation, mainly vinasse and stillage, respectively generated from sugarcane and corn ethanol production in flex plants. Both by-products require efficient treatment routes to avoid environmental side-effects to support energy recovery. Accordingly, the aim of this study was to evaluate the techno-economic potential of bioenergy (electric and thermal energy) production from the anaerobic digestion (AD) of vinasse and stillage. Three scenarios were defined: (a) Scenario 1, AD of vinasse; (b) Scenario 2, AD of stillage; and (c) Scenario 3, AD of vinasse and stillage in an integrated process. From the results, the methane production was estimated at 3.8×10^6 m^3 $year^{-1}$ considering the AD of stillage and vinasse in Scenario 3. The electricity and thermal energy generation was estimated as 14.61 GWh $year^{-1}$ and 1.37×10^5 GJ $year^{-1}$, respectively. This energy would mitigate 1096.05 and 7659.27 ton CO_{2eq} $year^{-1}$ when replacing fossil fuel energy. The profitability analysis indicated a positive net present value in the scenarios evaluated, however, the highest value was achieved for Scenario 3 (7,890,407.44 USD). For the integrated process, an internal return rate of 86.87% and a payback of 0.68 year were observed. The sensitivity analysis showed that the project profitability is highly dependent on electricity and thermal energy selling prices. In conclusion, AD demonstrated to be a feasible alternative for vinasse and stillage management in an integrated process, being a sustainable technology to the circular economy transition and energy matrix decarbonization.

1. Introduction

The imminent depletion of fossil fuels, the generation and increasing accumulation of waste, and climate change are some of the main problems that the current society must face. In response to this, the concepts of circular economy, bioeconomy, and more recently, circular bioeconomy have been emerging. The linear economy occurs when raw materials are used to make a product, and any waste is thrown away. Otherwise, circular economy is based on the conservation of by-products value, where new materials and resources are placed in the market for an extended period with reduced waste generation [1]. Besides reducing negative environmental side-effects, circular economy stimulates new business opportunities [2]. Whenever the economy comprises renewable biological resources to produce food, materials, and energy, it is defined as bioeconomy [1].

However, unifying principles for a global bioeconomy, including several stakeholders as international policy organizations, multilateral trade negotiators, and the corporate sector, are necessary. Bioeconomy knowledge-base is the production and utilization of biological resources, innovative biological processes, and principles to sustainably provide goods and services across all the economic sectors. Circular bioeconomy was conceptualized merging circular economy and bioeconomy concepts [3]. Stegmann et al. [4] defined circular bioeconomy by focusing on the sustainable, resource-efficient valorization of biomass in integrated production chains while using by-products and waste to optimize the production of value-added products from biomass. Thereby, biorefineries are perceived as essential infrastructure items within such concepts [5]. Biomass and by-products from industrial processing can be used as integral components to generate various bio-products, biochemicals, and bioenergy, and their use in integrated biorefineries can

* Corresponding author.
E-mail address: montserrat.perez@uca.es (M. Pérez).

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be a strategy to achieve sustainable development and profitability [6].

In Brazilian biorefineries, ethanol production for fuel purposes has become a robust, economically viable, and sustainable industrial bioprocess [7]. The reasons for the replacement of fossil fuels by biofuels are marked by the pressure of oil prices and environmental side-effects such as global warming [8]. Ethanol has been considered a better choice as one of the most promising renewable fuels [9]. Brazilian main biofuel crop is sugarcane (30% of net production value), followed by soybean (29%), and corn (4%) [10]. First-generation ethanol production from sugarcane presented an increase of 33.3 billion liters in 2018/2019 harvest season [11].

Ethanol can be obtained by fermentation of sugars from raw materials such as corn, sugarcane, and lignocellulose [12]. In Brazil, for more than 30 years, sugarcane is the most common feedstock for ethanol production. However, the flex plant models make it possible to produce ethanol by processing sugarcane and corn. Thus, arises industrial interest for ethanol production from corn in Brazil [13]. One of the most benefits of flex plants would allow extending operations beyond the current sugarcane harvest season. Additionally, sugarcane produces less ethanol than corn by weight. For 1 ton of sugarcane, it produces between 80 and 90 L of alcohol, while 1 ton of corn yields more than 400 L [14]. Otherwise, approximately 6000 L ha^{-1} of sugarcane ethanol is produced against 3500 L ha^{-1} of corn [15]. Furthermore the current market value of corn cannot compete with sugarcane. Yet, the cost to produce corn ethanol has been higher than that of sugarcane ethanol [16]. Besides ethanol production, to meet the aims of circular bioeconomy it is necessary to consider waste generation and its future valorization [17]. Biorefineries generate a considerable amount of biodegradable solid or liquid by-products, which are raw materials for other co-products. With the transformation of organic materials via anaerobic digestion (AD), fermentation, or composting technologies, products like biogas, biofertilizers, and secondary biochemicals can be obtained, such as volatile fatty acids [18]. AD is one of the most sustainable methods for treating organic materials and produce bioenergy, especially due to its low investment costs and high versatility [19]. Moreover, the main final products obtained from AD are biogas and fertilizer, which can be used for energy recovery and soil amendment, respectively [20–22]. Nonetheless, bioenergy production from AD can be deployed to facilitate a transition to the circular economy and to reduce greenhouse gases (GHG) emissions. The literature reports that the installation and operation of AD technology in sugarcane mills and distilleries reduced the GHG emissions of the ethanol production [23,24], which is an environmental benefit to achieve the sustainable development goals established by the United Nations Framework Convention on Climate Change (UNFCCC) [25].

Regarding the by-products generated in ethanol flex plants, vinasse is the liquid by-product from sugarcane ethanol production, reaches, on average, 10–15 L for each liter of ethanol produced [26–28]. This by-product is usually disposed of as fertilizer in sugarcane crops because of the presence of macronutrients in its composition, such as nitrogen (N), phosphorus (P), potassium (K), and organic matter [28]. An alternative for sugarcane vinasse is the management in anaerobic reactors, reducing its organic load and neutralizing its pH, while maintaining most of its nutrients for agricultural use [28]. From an environmental perspective, the digested vinasse is less harmful to the environment [22,29]. The biogas produced can be used in the ethanol plant to dry the yeast and to operate gas turbines combined with an electric generator. In addition, biogas can replace part of the fossil fuels used in the agroindustry during harvesting if applied in boilers to generate steam and to supply sugarcane milling [30,31]. Regarding corn ethanol production, the by-product obtained is called stillage or whole stillage. The whole stillage is separated into a liquid fraction (thin stillage) and a solids fraction, called wet distillers' grains with soluble (WDGS), by centrifugation. WDGS are dried for producing distillers dried grains with soluble (DDGS), the main co-product from corn fermentation, which is usually used as animal feed, given its high protein and vitamin contents [32,33]. On average, 386 kg of DDGS are produced per ton of corn [16]. In the last years, a growth in DDGS production has occurred. In Brazil, despite the higher carbon footprint associated to cattle farming [34], this activity is a national relevant economic sector, traditionally based on extensive grazing system (the industry *status quo*) [35]. DDGS is sparely employed for cattle feed being mainly used for swine [36–38]. As consequence, new research areas have emerged for alternative uses of DDGS, among them AD to produce energy for corn ethanol plants [39]. Notwithstanding, Ao et al. [40] suggested solid vinasse as a promising feedstock for AD due to its large amount of biodegradable components. They defined solid vinasse as a mixture obtained from the fermentation of a mixed feedstock composed of sorghum, corn, and wheat. Oppositely than sugarcane vinasse, there is a lack in the literature regarding the correct management of stillage for bioenergy and fertilizer production, and studies in an integrated process can be a solution to elucidate gaps for this industrial sector.

Based on the aforementioned, this study aimed to determine the techno-economic potential of bioenergy recovery from by-products from sugarcane and corn ethanol production in a flex plant. Additionally, the potential methane production by AD, maximum methane yield, theoretical maximum methane yield, electricity, thermal energy generation, and economic profitability were estimated for the industrial process. Hence, the assessment of the bioenergy generation from ethanol by-products by AD could enlighten the technological integration as an innovative technological route to rethink ethanol production and to reinforce the circular economy concept.

2. Material and methods

2.1. Flex plant process diagram

A flowchart for a Brazilian flex ethanol mill (operating with sugarcane and corn) is showed in Fig. 1. Beyond, there are other possible designs and plants that recover the oil from distillers' soluble, the flowchart represents the process adopted in the case study, operating with dry milling.

The process of ethanol production from sugarcane comprises the following steps: (a) firstly, sugarcane is milled with water, producing juice and bagasse; (b) the bagasse is burnt to produce energy; (c) the sugarcane juice is subjected to fermentation; and (d) the fermented mash is sent to the distillation unit, where ethanol is separated from vinasse. For ethanol production from corn, the steps are: (a) the corn is milled to obtain flour; (b) before the fermentation, this flour is mixed with water and enzymes; (c) after the fermentation, the mash is fed to a distillation column; (d) ethanol is separated from the stillage, which is sent to a centrifuge to separate thin stillage and WDGS; and (e) the last is dried to produce DDGS.

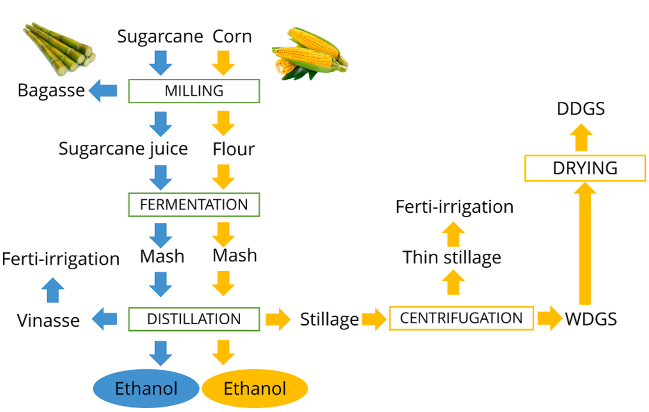

Fig. 1. Ethanol production flowsheet from sugarcane and corn in a flex plant.

2.2. Case study and scenarios description

A typical ethanol flex plant located in Mato Grosso Federative State of Brazil was used as a case study. This plant processes 2880 ton day^{-1} of sugarcane and 1210 ton day^{-1} of corn. The harvesting seasons were assumed as six months for sugarcane (from November to April) and four months for corn (from May to August). The input parameters and the production data are presented in Table 1.

This study proposes the AD implementation in a flex plant, to produce biogas and its subsequent burnt to generate electrical and thermal energies. The proposed flowchart for ethanol production from sugarcane and corn in a flex plant with AD adoption is presented in Fig. 2. The further techno-economic assessment was conducted for the following scenarios: (a) Scenario 1, AD of vinasse; (b) Scenario 2, AD of stillage; (c) Scenario 3, AD of vinasse and stillage in an integrated process, as illustrated in Fig. 2.

2.3. Process design for vinasse and stillage AD

2.3.1. Raw material characterization

By-products from a typical ethanol flex plant, vinasse from sugarcane ethanol production and stillage from corn ethanol production were used to evaluate the potential of methane production and its technical–economic evaluation. From the scientific literature, the main physicochemical characteristics of vinasse and stillage were presented in Supplementary Material. In general, both materials present a low pH, around 4. The Total Chemical Oxygen Demand (TCOD) reported for vinasse was approximately 30 g L^{-1}, and TCOD values for stillage were above 100 g L^{-1}.

2.3.2. Industrial arrangement for AD

The proposed block diagram and industrial arrangement for bioenergy production with AD adoption is presented in Fig. 3. Vinasse or stillage generated after ethanol production is collected and destined to an equalizer tank where the pH is adjusted to approximately 7.5, by the addition of NaOH. The optimal pH for AD ranges from 6.5 to 8.5 because the methanogenic phase is inhibited below or above these values [20]. The substrates are introduced into the digester, where AD is carried out, and generating two final products: biogas and digestate. The digestate is collected in a circular decanter to remove the water and to, eventually, be used as soil fertilizer. The fertilizer sales have not been considered in the economic analysis. A combined heat and power (CHP) engine was assumed to convert biogas into electrical and thermal energy. Before biogas conversion, it is drained and dried because most CHP present maximum limits for hydrogen sulphide, halogenated hydrocarbons, and siloxanes contents [41].

2.3.3. Theoretical biogas production

The theoretical calculation of biogas and methane production, expressed as potential biogas production rate (pBPR) and potential methane production rate (pMPR), followed Eqs. (1) and (2) [42], respectively.

$$pBPR = RFR \times TCOD_{residue} \times ER_{COD} \times BY \quad (1)$$

Table 1
Input parameters and production data of the flex plant.

Parameters*	Unit	Sugarcane	Corn
Feedstock flow rate	ton day^{-1}	2880	1210
Harvest period	day	180	120
Ethanol production	L day^{-1}	184,320	471,900
Vinasse/ethanol proportion	$L_{vinasse}\,L_{ethanol}^{-1}$	13	–
Stillage/ethanol proportion	$L_{stillage}\,L_{ethanol}^{-1}$	–	20
Vinasse flow rate	m^3 day^{-1}	2396	–
Stillage flow rate	m^3 day^{-1}	–	9438

*Field data obtained from the flex plant used in the study case.

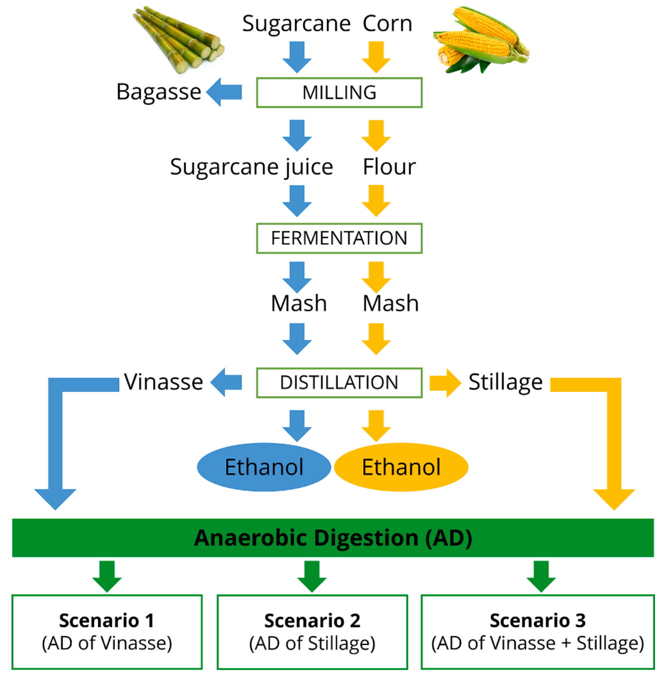

Fig. 2. Ethanol production from sugarcane and corn in a flex plant with the anaerobic digestion for vinasse and stillage management and energy recovery.

$$pMPR = pBPR \times f_{CH_4} \quad (2)$$

where pBPR is the potential biogas production rate (m^3 biogas day^{-1}); pMPR is the potential methane production rate (m^3 CH_4 day^{-1}); RFR is the residue flow rate (m^3 day^{-1}); $TCOD_{residue}$ is the total COD of the residues (kg m^{-3}); ER_{COD} is the COD removal efficiency (%); BY is the biogas yield (m^3 biogas kg^{-1}$COD_{removal}$); and f_{CH4} is the fraction of methane in the biogas.

2.3.4. Potential of electric and thermal energy generation

The potential of electricity (EG) and thermal energy (TE) generation was calculated using Eq. (3) [43] and Eq. (4) [44]:

$$EG = Q_{biogas} \times LCV_{CH_4} \times f_{CH_4} \times n_e \times n_g \times F_c \quad (3)$$

$$TE = Q_{biogas} \times LCV_{CH_4} \times f_{CH_4} \times \eta_H \quad (4)$$

where EG is the electricity generation (MWh ton^{-1}); TE is the thermal energy (MJ day^{-1}); Q_{biogas} is the volume of biogas (m^3); LCV_{CH4} is the lower calorific value of methane (8500 kcal m^{-3}); f_{CH4} is the fraction of methane in the biogas; n_e is the engine efficiency (45%); n_g is the generator efficiency (95%); ηH is the heat recovery efficiency (%), assumed as 50%; and F_c is the correction factor due to uncertainties (assumed as 90%) - this factor takes into account the losses in the pipes, mechanical couplings, the presence of other gases not fully quantified, and other factors that lead to losses in the final energy generated.

2.3.5. Avoided GHG emissions

The avoided greenhouse gas (GHG) emissions (A_{GHG}) indicate the potential reduction of GHG emissions by the production plant considering the replacement of external energy sources for the electric and thermal energies generated from the biogas burning in a CHP. The avoided GHG emissions for electricity and heat were estimated according to Eqs. (5) and (6) [45]:

$$A_{GHG_{EG}} = 0.075 \times EG \times t \quad (5)$$

$$A_{GHG_{TE}} = 0.056 \times TE \times t \quad (6)$$

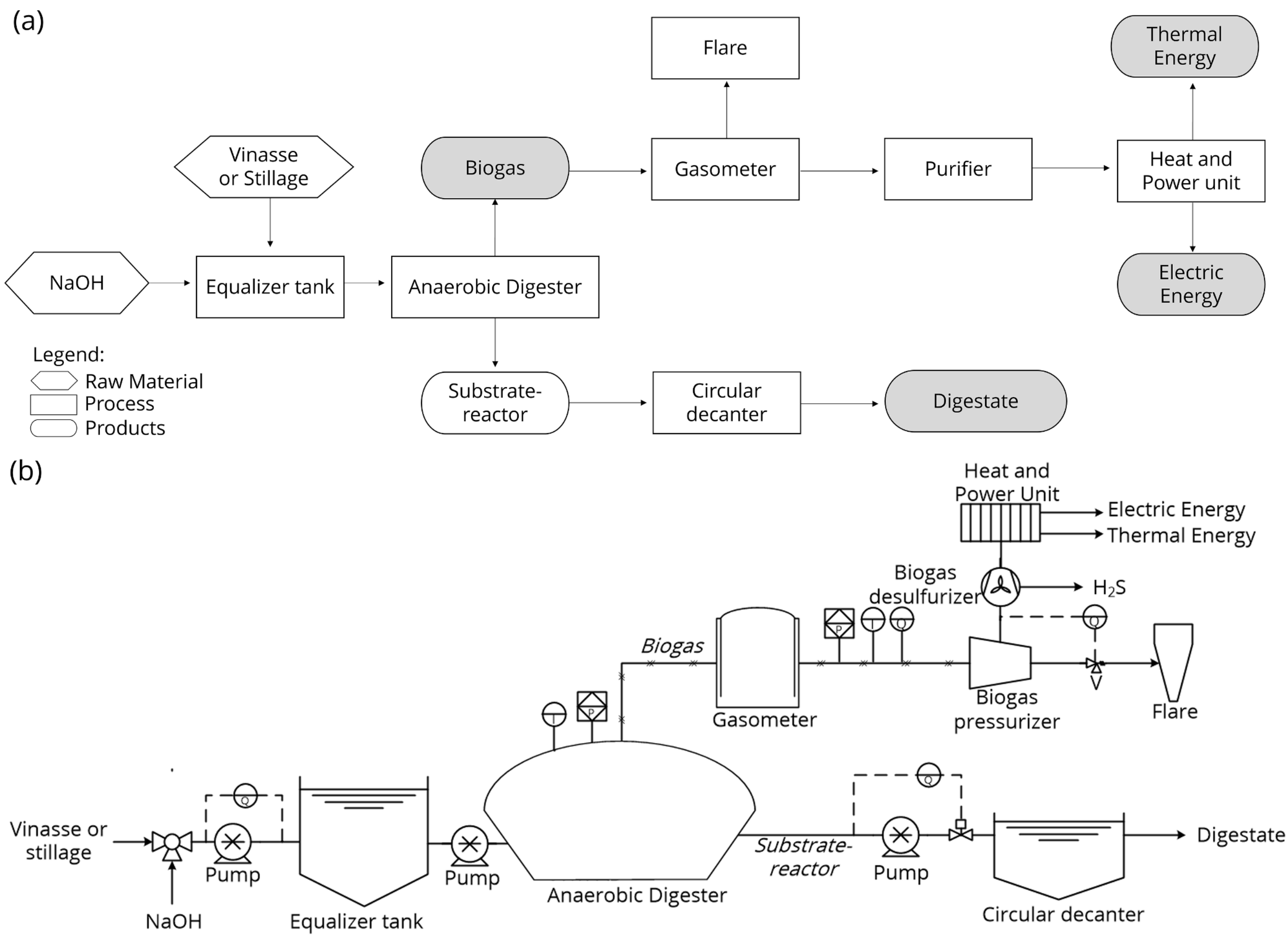

Fig. 3. Industrial arrangement for bioenergy production from vinasse and stillage AD. (a) Block diagram flowsheet. (b) Process flow diagram.

where 0.075 is the emission factor in tons of CO_{2eq} MWh^{-1} for 2019 Brazilian electric energy generation based on the respective mix of electricity source (annual mean value (from January 2019 to December 2019), reported in the official data of the Ministry of Science, Technology, Innovation and Communication [46]; EG is the electricity generation potential (MWh ton^{-1}); 0.056 is the emission factor of heat energy (assumed as the default value of natural gas, 0.056 tCO_{2eq} $GJ^{-1}$from [47] guidelines for GHG inventories); TE is the thermal energy (MJ day^{-1}); and t is the time of operation (assumed as 7200 h).

2.4. Techno-economic evaluation

The techno-economic analysis is widely used to compare the cost-benefit of a well-established process with existing or developing technologies to infer if economic feasibility can be achieved [48]. The assumptions and considerations for techno-economic evaluation are presented in Table 2.

In this case study, the revenues were established as follows: 100% of the electric energy generated in the CHP engine is sold to the grid, and 100% of the thermal energy is sold to the industry to replace natural gas in boilers.

2.4.1. Itemized cost estimation

The fixed capital investment (FCI) is related to the expenses for implementing the industrial arrangement described in Section 2.3.3. Equipment installation costs were collected from the current Brazilian market prices. A covered lagoon digester was selected for being the most robust and cheap compared to others, such as continuously stirred tank reactors or up-flow anaerobic sludge blanket [50]. Table 3 describes the cost of equipment for the AD implementation and bioenergy recovery, considering the industrial process described in Fig. 3b.

Table 2
Assumptions adopted for the case study.

Parameters	Units	Value	Reference
Selling prices			
Electric energy	USD MWh^{-1}	60.56	[a]
Thermal energy	USD MJ^{-1}	0.0082	[a]
Costs			
Vinasse	USD m^{-3}	0.10	[b]
Stillage	USD m^{-3}	0.15	[b]
Water	USD m^{-3}	0.35	[a]
NaOH	USD kg^{-1}	0.53	[a]
Electric energy	USD MWh^{-1}	60.56	[a]
Operational labor cost	USD h^{-1} worked	3	[a]
Economic inputs			
Project lifetime	year	25	[b]
Annual depreciation rate	%	10	[b]
Annual tax rate	%	25	[b]
Attractiveness rate	%	15	[b]
Time operation plant	day $year^{-1}$	320	[b]
Financing (external capital)	%	100	[b]
External capital (bank financing period)	year	10	[b]
Annual interest rate	%	8.5	[b]
Average exchange rate for year 2020	USD BRL^{-1}	3.94	[c]

[a] [49].
[b] Brazilian market price.
[c] IPEA (2020).

Table 3
Cost of equipment for the AD implementation.

Item	Unit cost	Quantity	Total cost (USD)
Pump	1620.83 USD	3 unit	4862.50
Automatic valves	402.66 USD	3 unit	1207.97
Temperature probe	174.11 USD	2 unit	348.22
Flow meter	2570.75 USD	3 unit	7712.26
pH probe	1110.10 USD	1 unit	1110.10
Equalization tank	40 USD m^{-3}	6000 m^3	240,000.00
Pipe	10.56 USD m	100 m	1056.00
Digester	345,681.81 USD	1 unit	345,681.81
Flare	3000 USD	1 unit	3000.00
Biogas pressurizer	12,000 USD	1 unit	12,000.00
Biogas desulfurizer	68,000 USD	1 unit	68,000.00
Heat and power unit	44,000 USD	1 unit	44,000.00
Circular decanter	40 USD m^{-3}	6000 m^3	240,000.00
Landscaping	30 USD h^{-1}	30 h	900.00

The cost of raw material (CRM) consists of the costs required to prepare the raw material and the costs of the chemicals. CRM of vinasse and stillage was estimated as 0.1 and 0.15 USD m^{-3}, respectively. This difference is because there is no alternative to vinasse other than soil fertilizer. However, stillage can be used to produce DDGS with commercial value. CRM of water and NaOH were estimated as 0.35 USD m^{-3} and 0.53 USD kg^{-1}, respectively. Cost of operation labor (COL) is related to labor (manpower and wages), three operational shifts with one worker/shift (3 workers day^{-1}) were assumed. COL was assumed as 3 USD h^{-1} worked [49]. Cost of utilities (CUT) considers the energy used (0.06 USD kWh^{-1}) in the process and the water for cleaning (0.35 USD USD m^{-3}), both considering the current Brazilian market prices. Cost of waste treatment (CWT) is the residue generated by the process, which was established as the capital necessary for implementing the process for digestate upgrade.

2.4.2. Cost of manufacturing

After determining the main process costs, it is necessary to calculate the cost of manufacturing (COM) to carry out an economic analysis of bioenergy production. COM was calculated as the sum of the main process' components (FCI, COL, CUT, CWT, and CRM) according to Eq. (7) [51]:

$$COM = (0.304 \times FCI) + (2.73 \times COL) + [1.23 \times (CUT + CWT + CRM)] \tag{7}$$

2.4.3. Profitability analysis

The project feasibility was analysed from the following indicators: Gross Margin (GM); Net Margin (NM); Net Present Value (NPV); Internal Rate of Return (IRR); Return on investment (ROI); and Payback. GM is the difference between the revenue and the costs of the goods sold, while NM is the GM minus operational expenses and all other expenses. NPV is the difference between the present value of cash inflows and outflows over a period of time. NPV is used to determine the profitability of a project, and it can be calculated by Equation (8). IRR is the discount rate that sets the NPV equal to zero and can be calculated by Equation (9).

$$NPV = \sum_{t=1}^{n} \frac{FC_t}{(1+i)^t} - I_0 \tag{8}$$

$$NPV = \sum_{t=1}^{n} \frac{FC_t}{(1+IRR)^t} = 0 \tag{9}$$

where FC_t is the cash flow in period "t" time; "t" is the period in which the money will be invested; "n" is the project lifetime; "i" is the cost of the capital; and I_0 is the initial investment.

ROI is a decision tool from a business perspective, used for capital budgeting and to evaluate the performance of an investment project, estimated by Eq. (10).

$$ROI\ (\%) = \frac{Annual\ net\ profit}{Total\ capital\ investment} \tag{10}$$

Payback is the period in years required to recover the original investment (Eq. (11)).

$$Payback(y) = \frac{Total\ capital\ investment}{Annual\ net\ profit} \tag{11}$$

2.5. Sensitivity analysis

A sensitivity analysis was elaborated to evaluate the relative importance of input parameters over the economic performance of the competing scenarios. NPV and IRR were the profitability factors selected for the analysis and modeled in the cash flow. The tornado diagram was performed for a better insight, with a change of ±30% on each parameter once at a time.

3. Results and discussion

3.1. Theoretical biogas production analysis

Biogas and methane production were calculated based on the AD of vinasse and stillage (Fig. 4). The biogas volume was estimated as 6.8×10^6 m^3 $year^{-1}$ for the harvest season of both feedstocks, sugarcane and corn, which would yield a methane production of 3.8×10^6 m^3 $year^{-1}$ (Table 4).

3.2. Potential of electric and thermal energy generation

The potential of electricity (EG) and thermal energy (TE) generation were calculated for the volume of biogas of each by-products studied (vinasse and stillage), and the results were summarized in Table 5. The AD of vinasse (Scenario 1) can produce 8.24 GWh $year^{-1}$ of electricity and 77,121 GJ $year^{-1}$ of thermal energy, which is higher when compared with the AD of stillage in Scenario 2 (6.37 GWh $year^{-1}$ and 59,651 GJ $year^{-1}$, respectively for electricity and thermal energy). In 2014, the consumption of electrical energy in Mato Grosso Federative State was 8289.6 GWh [52], and therefore, the electrical energy generated by both wastes (14.61 GWh $year^{-1}$) could supply 0.2% of the annual power in this State. The value generated ($1.37 \cdot 10^5$ GJ $year^{-1}$) represents 0.1% of the energy demand in Mato Grosso State regarding thermal energy. Otherwise, a common ethanol flex plants demands high amount of energy, and the bioenergy produced from AD of stillage and vinasse can be used to supply the facility energy requirements, contributing to a lower carbon footprint of this industrial sector.

3.3. Avoided GHG emissions

From the potential electricity and thermal energy generated from

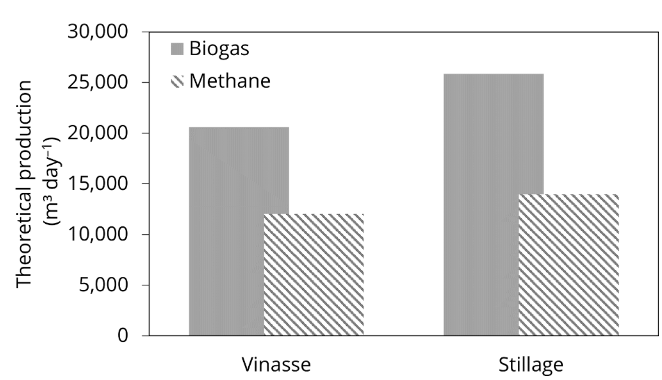

Fig. 4. Theoretical biogas and methane production for vinasse and stillage.

Table 4
Theoretical biogas production for the vinasse and stillage.

Parameters	Units	Vinasse	Stillage
RFR	m^3 day^{-1}	2396	9438
$TCOD_{residue}$	kg m^{-3}	33.69	365
ER_{COD}	%	60.70	85.10
Biogas yield	m^3 kg^{-1} $COD_{removal}$	0.43	0.0083
f_{CH4}	%	58.40	54.00

Table 5
Technical parameters calculated for the scenarios studied.

Parameters	Units	Scenario 1	Scenario 2	Scenario 3
Electricity	MWh day^{-1}	45.78	53.11	98.89
	GWh $year^{-1}$	8.24	6.37	14.61
Thermal energy	GJ day^{-1}	428.45	497.10	925.55
	GJ $year^{-1}$	77,121	59,651	136,772

biogas burning in the CHP engine (Table 5), the avoided GHG emissions were estimated. The yearly CO_{2eq} emissions avoided for both alternatives were shown in Table 6. Total emissions avoided would reach 1,096.05 and 7,659.27 ton CO_{2eq} in one year for electricity and heat generation, respectively. The emissions avoided by replacing natural gas for heat generated from biogas for both vinasse and stillage are outstanding higher than the recorded value for converting biogas into electricity. These results are in line with those obtained by Ferreira et al. [53] for heat recovered from biogas from paper mill wastewater AD versus natural gas. Beyond, the GHG emissions in the production and use of ethanol are estimated at 29 gCO_{2eq} MJ^{-1} [24], and the avoided GHG emissions with the implementation of AD for the treatment of vinasse and stillage can be an alternative to reduce the carbon footprint of ethanol flex plants.

3.4. Economic analysis

3.4.1. Cost's discrimination

The equipment cost for the AD process implementation was used as the basis for calculating the FCI. Considering all these costs, the total FCI was 972,230.22 USD. The highest cost comes from the digester, which represents 35.56 % of the FCI. Beyond, Table 7 presents the yearly capital expenditures (CAPEX) and the operating expenses (OPEX) for the five major costs. In general, it is possible to observe that only CRM increased in Scenario 3, since this process requires the acquisition of stillage and vinasse. The COL (23,040.00 USD $year^{-1}$), CUT (5903.20 USD $year^{-1}$), CWM (24,459.00 USD $year^{-1}$), and FCI (97,223.00 USD $year^{-1}$) are equivalent for the three scenarios since these costs are mandatory for the process implementation.

Notwithstanding, the contribution of each cost discriminated over the COM were presented in Fig. 5. As can be observed, the annual costs related to the project implementation (FCI) were the most significant (50.18%) for Scenario 1. However, the CRM represents the main percentual influence on the COM for the other scenarios. For Scenario 2 and Scenario 3, the CRM was 53% and 58.58%, respectively. These results could be due to two reasons: in Scenarios 2 and 3, the volume of by-product (raw material for AD) increases concerning Scenario 1, and the price of stillage (Scenarios 2 and 3) is higher than vinasse one (Scenarios 1 and 3). According to Pereira et al. [54] and Zabot et al. [55], raw materials generally have the most significant contribution to COM. Beyond, in AD process the CRM and FCI are the main contributors to COM [49]. COM was evaluated both for electricity and thermal energy generation (Fig. 6). The maximum value of COM was reached for Scenario 2 for electricity (53.18 USD MWh^{-1}) and thermal energy (USD MJ^{-1}), respectively two-fold higher than Scenario 1 and 3. In the three scenarios simulated, the COM obtained was lower than the market prices. These results are the first approach to determine the possibility of positive profitability since a positive COM was obtained when compared with the implementation and operational costs, indicating the possibilities to determine the project's feasibility.

Table 6
Avoided GHG emissions for the scenarios studied.

Parameters	Units	Scenario 1	Scenario 2	Scenario 3
Avoided $GHG_{electricity}$	ton CO_{2eq} $year^{-1}$	618.02	478.03	1096.05
Avoided $GHG_{thermal\ energy}$	ton CO_{2eq} $year^{-1}$	4318.78	3340.49	7659.27

3.4.2. Annual sales and cash flow

For the economic analysis, it is assumed that a CHP engine converts the biogas into electrical and thermal energy, and the sale of 100% of this energy was assumed. The annual sales for the three scenarios studied are shown in Table 8. As expected, Scenario 3 is the most advantageous since the revenue corresponds to the sum of those generated in Scenarios 1 and 2. Accordingly, the electrical and thermal energy generated can provide annual revenues of 886,096.50 and 450,256.01 USD, respectively.

The current assets calculated are presented in Fig. 7. From the annual sales, it is necessary to deduct the implementation costs, depreciation, interest rate, and income tax. As shown in Fig. 7, the current assets of the project were negative in the first year in all the scenarios studied. They began to present positive values and an increasing trend throughout the project's lifetime. The highest value was reached in Scenario 3.

3.4.3. Profitability indicators

Profitability indicators for the three scenarios studied are presented in Table 9. NPV has a positive value in all cases, indicating that the project has added wealth to the industry, suggesting that it has a high financial return potential. The highest NPV was reached for Scenario 3 with a value of 7,890,407.44 USD, with the payback occurring within the first year. This NPV is 1.7 and 3.4 higher than Scenarios 1 and 2, respectively. The economic parameters associated with Scenario 3 were higher than the other scenarios, offering better profitability. In Scenario 3, the IRR increased by 59% and 191%, and the ROI was increased by 58 % and 170 % compared to Scenarios 1 and 2, respectively. The greater the project's benefits, the larger the IRR of a project [29]. The payback period for all scenarios was 1/9 of the project lifetime (25 years), which shows the financial viability of the designed plant. Finally, Scenario 3 reached the highest profitability among the three investigated scenarios in terms of all profitability indicators, hence considered as an optimistic and more competitive scenario in this case study.

3.5. Sensitivity analysis

Sensitivity analysis was performed for the three scenarios, aiming to discuss the market prices variability influence on the profitability indicators. The parameters selected to carry out the sensitivity analysis were the price of the raw material (vinasse and stillage) and the FCI. These parameters were selected because they are the most representative costs of the COM as aforementioned. Likewise, the variation in the price of electricity and thermal energy was also analysed to consider possible fluctuations in the market price. Fig. 8 shows the sensitivity analysis results for the parameters' influence on NPV and IRR.

Regarding NPV, the results show that variations in the electricity selling price had the highest impact. The increase in electricity energy price increased the NPV to 9,963,873.25 USD, while the decrease in the parameter value decreased the NPV to 5,816,941.63 USD. Although with a lower impact, the price of thermal energy also affected the project profitability. Oppositely, FCI was the most significant parameter influencing the IRR. By decreasing the FCI, the IRR increased from 86.87 % to 123.18 %. This would mean an improvement in the profitability since

Table 7
Costs discrimination for the scenarios.

Parameters	Cost classification	Units	Scenario 1	Scenario 2	Scenario 3
Feedstock	CRM	USD year^{-1}	43,128	169,884.00	213,012.00
Operational labor	COL	USD year^{-1}	23,040.00	23,040.00	23,040.00
Water for cleaning	CUT	USD year^{-1}	1,058.40	1,058.40	1,058.40
Electric energy	CUT	USD year^{-1}	4,844.80	4,844.80	4,844.80
Digestate management	CWM	USD year^{-1}	24,459 0.00	24,459 0.00	24,459.00
Implementation	FCI	USD year^{-1}	97,223.00	97,223.00	97,223.00

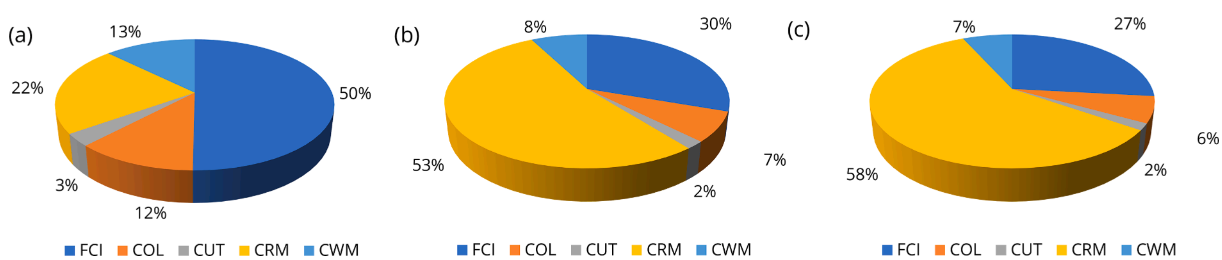

Fig. 5. Contribution of each cost discriminated over the COM. (a) Scenario 1; (b) Scenario 2; and (c) Scenario 3.

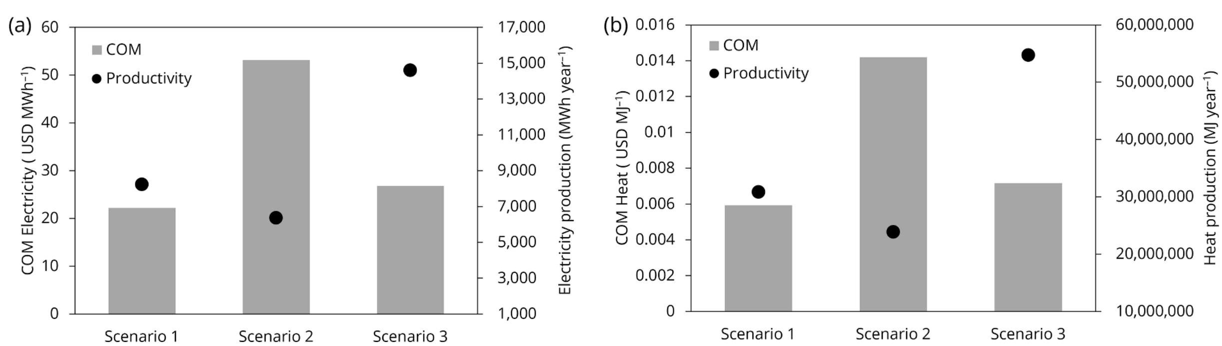

Fig. 6. Cost of manufacture and productivity of electricity and thermal energy (heat) for the three scenarios. (a) Electricity production; (b) Heat production.

Table 8
Annual sales for the scenarios studied.

Parameters	Units	Scenario 1	Scenario 2	Scenario 3
Electricity	USD year^{-1}	499,756.00	386,340.50	886,096.50
Thermal energy	USD year^{-1}	253,882.83	196,373.18	450,256.01
Total	USD year^{-1}	753,638.83	582,713.68	1,336,352.51

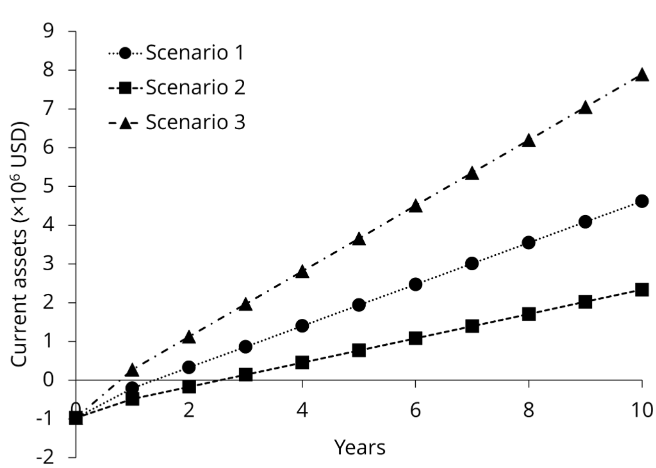

Fig. 7. Current assets for the scenarios studied.

Table 9
Profitability indicators for bioenergy production from AD in the scenarios studied.

Parameters	Unit	Scenario 1	Scenario 2	Scenario 3
GM	%	90.44	65.88	81.89
NM	%	56.86	35.23	55.24
ROI	%	55.19	32.22	87.03
IRR	%	54.47	29.86	86.87
Payback	years	1.39	2.55	0.68
NPV	USD	4,619,370.74	2,335,484.57	7,890,407.44

the IRR should be as higher as possible to undertake a project [55]. As well as on the NPV, variations in the price of electrical and thermal energy also have a high impact on the IRR. By contrast, when the price of vinasse and stillage was changed, no significant variations in IRR and NPV were observed.

3.6. Concluding remarks and perspectives

The link between ethanol processing industry, livestock and swine farming in the State of Mato Grosso is still incipient. Hence, further research on the economics, environmental and social aspects are necessary to establish the most suitable technological routes for the industrial by-products management for sugarcane and corn flex mills. Medium and long-term state policies, and clean development mechanisms aiming to promote the bioenergy Brazilian market and energy matrix decarbonization are powerful strategies. The most recent

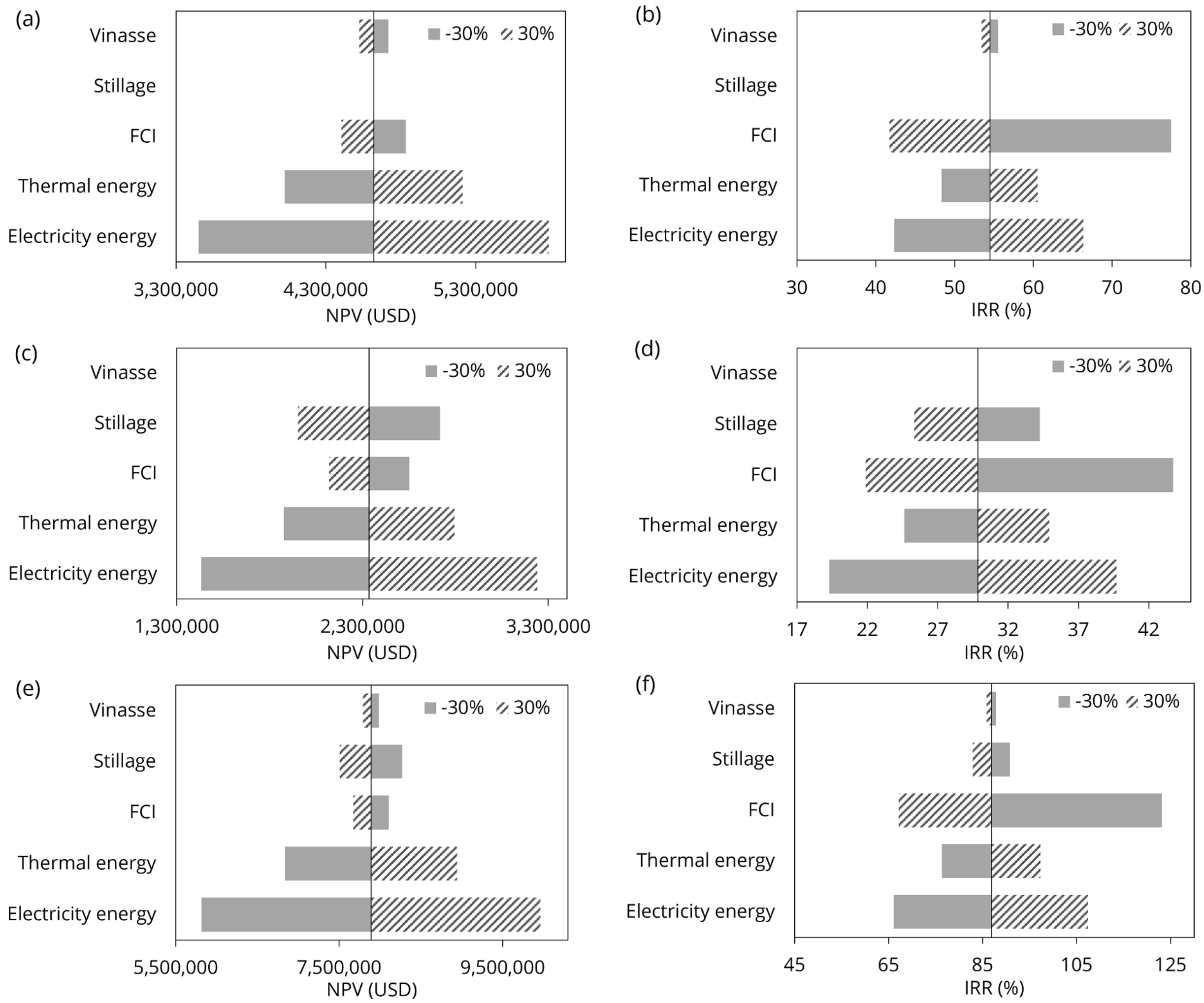

Fig. 8. Sensitivity analysis for essential parameters in AD of stillage and vinasse. (a) Scenario 1, NPV; (b) Scenario 1, IRR; (c) Scenario 2, NPV; (d) Scenario 2, IRR; (e) Scenario 3, NPV; (f) Scenario 3, IRR.

Brazilian State Policy towards the bioenergy economy is called *RenovaBio* [56,57], established to achieve the Paris Agreement's Brazilian daring commitments. *RenovaBio* involves all the biofuels, especially ethanol, second-generation ethanol, biodiesel, biogas, and biomass as contributors to the country energy security and decarbonization strategy. Moreover, ethanol is used up in a mixture in gasoline in different proportions [58], being a viable fuel alternative to reduce dependence on oil, lower energy costs and reduce GHG emissions. From the biomass perspective, AD, a worldwide disseminated technology recognized as a cheap one [59], is potentially suitable and feasible to close flex mills' circularity in bioenergy projects. The state of Mato Grosso has a strong agro-industrial vocation and can also play an important role in the Brazilian energy sector, including the rational use of renewable energy from biomass and agro-industrial by-products. Residual biomass is an abundant source of bioenergy and biomaterials and its recovery from AD can foster the development of a circular economy [60,61], adding value to materials by means of a well-known, flexible, and cheap technology. In addition to reducing the acquisition costs mineral fertilizers (NPK) and GHG emissions from the soil, the use of digestate for crops fertigation, completes the circularity of AD adoption, maximizes internal nutrient recycling, and reduces the dependence on external NPK non-renewable resources [22,62].

4. Conclusion

The potential of methane generation from the vinasse and stillage generated in a flex ethanol plant was estimated. The electricity (14.61 GWh year^{-1}) and thermal (1.37 $\times$ 10^{5} GJ year^{-1}) energy generated by the biogas burning in a CHP from both by-products anaerobic digestion could replace 0.2% and 0.1%, respectively, of the energy demand of Mato Grosso State. The anaerobic digestion of vinasse and stillage together was the most optimistic scenario due to its highest profitability among the other two scenarios evaluated (for vinasse or stillage alone AD). For the best scenario, 7.890.407,44 USD and 86.87% were achieved for NPV and IRR, respectively. A large amount of ethanol production by-products could be readdressed as bioenergy employing a cheap and well-consolidated technology. AD showed to be potentially beneficial from technical and economic indicators, being a promising technology for industrial implementation in flex plants. Moreover, green technology can foster circular economy development and energy matrix decarbonization.

CRediT authorship contribution statement

Miriam Tena: Conceptualization, Investigation, Methodology, Writing - original draft. **Luz S. Buller:** Investigation, Methodology, Writing - original draft. **William G. Sganzerla:** Conceptualization, Investigation, Methodology, Writing - original draft. **Mauro Berni:**

Investigation, Writing - original draft. **Tânia Forster-Carneiro:** Project administration, Resources, Writing - review & editing. **Rosario Solera:** Project administration, Resources, Writing - review & editing. **Montserrat Pérez:** Project administration, Resources, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fuel.2021.122171.

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